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NEW APPROACH TO FIRE SAFE APPLICATION OF FIBRE-REINFORCED POLYMER REINFORCMENT FOR CONCRETE

Mohamed Kiari, Tim J. Stratford and Luke A. Bisby
BRE Centre for Fire Safety Engineering, School of Engineering, The University of Edinburgh
The King's Buildings, Mayfield Road, EH9 3JL, UK
m.kiari@ed.ac.uk tim.stratford@ed.ac.uk luke.bisby@ed.ac.uk

ABSTRACT:. The research presented in this paper investigates a new approach for FRP internal reinforcement, which exploits the higher tolerance to elevated temperatures of the fibres. FRP closed loops are made by continuous winding of fibres, thus negating the requirement for shear transfer between the concrete and the FRP reinforcement through bond. A series of four-point bending tests of beams reinforced with FRP loops, and others with otherwise identical straight FRP bars for comparison, were prepared and tested at ambient and elevated temperatures using gas radiant panels. Results confirm the effectiveness of the novel approach over straight bars. While in ambient tests specimens with different reinforcement types exhibited similar capacity, in heated tests using FRP loops reinforcement increased fire resistance time up to four in comparison with beams with straight bars. Failure in beams with straight bars occurred as bars pull-out at early stage of heating due to bond degradation. FRP loops on the other hand possess an additional interaction mechanics with concrete which enabled maintaining load transfer between concrete and reinforcement until failure occurred as reinforcement rupture..

1. Introduction

Fibre reinforced polymers (FRPs) are used as internal reinforced for concrete structures due to several advantages over steel, most notably lack of corrosion which can be a major problem regarding maintenance of structures incorporating steel reinforcement (Katz et al., 1999). An obstacle for FRP reinforcement to be used in wider range of structures remains the relatively poor performance of FRPs in elevated temperatures as would be experienced in case of fire. The comparatively poor fire performance of FRPs is attributed largely to bond deterioration, which occurs between FRP reinforcement and concrete due to polymer softening (McIntyre et al., 2014).

FRP consists of two main components: fibres and polymers. While the fibres can typically retain much of their strength at high temperatures, more than 800 °C for carbon fibres, polymer resins soften at much lower temperatures (ACI, 2015). Softening occurs in resins around their glass transition temperature, T_g, which can be as low as 60 °C for ambient cured systems (Green et al., 2007). The polymer resin is needed to fitful two functions within an FRP bar: (1) it allows load sharing between individual fibres; and (2) it forms the bar's surface and promotes bond with the concrete (ACI, 2015, Bisby et al., 2005). FRP bars may be made with various different surface configurations, including: sand-coated, ribbed, or helically wrapped, and in all of these the resin is a key component. If the resin softens at elevated temperatures, the means for force transfer (bond) between the concrete and the FRP reinforcement, through bars surface, is deteriorated – structural collapse may occur if there is no other means of load transfer (Green et al., 2007, ACI, 2015). The fire performance of FRP reinforcement within concrete elements has been investigated by a number of researchers, and severe bond strength reduction was observed. Bisby et al. (2005) reported that the bond strength of FRP reinforcement with concrete can be reduced to only 10% of it's ambient strength when exposed to temperatures between 100 and 200 °C. A similar trend was observed by (Katz et al., 1999) from pull-out tests on various types of FRP bars at elevated temperatures. Nigro et al. (2012) demonstrated that the fire performance of FRP reinforced concrete slabs could be improved if reinforcement ends were positioned in zones not directly exposed to fire, especially when the FRP bars were hooked at the ends.

2. Closed-Loop FRP Reinforcement

The current paper investigates the performance of a new arrangement of FRP internal reinforcement that is intended to enhance fire performance of FRP-reinforced concrete by reducing or removing reliance on stress transfer through bond. Instead of using straight FRP bars (an approach that was initially copied from steel-reinforced concrete design), the longitudinal FRP reinforcement is made from closed FRP loops, which are filament wound from long continuous fibres. The new design, using these filament wound FRP loops as internal reinforcement, does not rely only on bond for load transfer. Rather, it takes advantage of the fact that most FRP fibres are capable of sustaining a large proportion of their original strength at relatively high temperatures (more than 800 °C for carbon fibres). When the shear stress transfer bond mechanism of force transfer is lost or seriously reduced due to resin softening, tensile forces in the reinforcement (FRP fibres) can still be transferred to the concrete at the FRP loop ends.

The authors have previously demonstrated the concept of FRP loop reinforcement by conducting push-off tests upon concrete samples reinforced with straight, hooked, and looped carbon FRP (CFRP) reinforcement, where the reinforcement was exposed to temperatures up to 130 °C during testing (Kiari et al., 2013). Closed loops had strength up to three times higher than the straight bar specimens, and failed by rupture at a tensile strength exceeding the yield strength of 500 MPa steel reinforcing bars with the same cross sectional area as the CFRP reinforcement. The authors also previously performed four-point bending tests on concrete beams reinforced with either CFRP loops, or CFRP straight reinforcement spliced at mid-span within the heated region. Beams reinforced with straight, continuous CFRP reinforcement bridging the heated region were tested (with bar ends positioned in zones not directly exposed to fire). Results suggested that at elevated temperatures the beams with straight bars failed due to reinforcement debonding (i.e. anchorage) failure; this happened quickly when the anchorage zone was directly heated, and longer fire resistance times were achieved when unheated anchorage zones were provided. Insufficient overlapping length for specimens with CFRP loop reinforcement led to premature failure in form of concrete shearing along the loop overlapping region. This prevented the CFRP loops from sustaining significant loads at elevated temperatures (Kiari et al., 2015). The overlap length of the looped reinforcement is varied in the current paper, and results from a new series of four-point bending tests at ambient and elevated temperatures are presented and discussed.

3. Experimental Programme

A series of four-point bending tests was used to investigate the performance of a revised design of FRP reinforcement at both ambient and elevated temperatures. Twelve beam specimens were fabricated and tested under monotonic loading and transient localised heating in their midspan region.

3.1. Specimen Design

Test specimens were 1610 mm long (1470 mm span) with 160×150 mm cross-sections. They were reinforced with CFRP tension, steel shear, and steel compression reinforcement, as shown in Fig. 1. Specimens with straight FRP reinforcement were used to allow the performance of the closed-loop FRP reinforcement to be compared against a more conventional straight bar design. CFRP reinforcement in all specimens, both looped and straight bar, had the same sectional area, fibre content, and splice length. Also, for all specimens the splice was positioned within the heated region in Fig. 1. The 28-day cube and split cylinder strengths of the concrete were 24 MPa and 1.46 MPa, respectively. The concrete cover to the tensile reinforcement was 28 ± 2 mm. Specimen types (with a naming scheme that follows on from a previous test series) were:

E. beams with spliced CFRP closed loops, without any shear reinforcement in the loop overlapping zone;
F. beams with spliced CFRP closed loops, but with shear reinforcement in overlapping zone; and
G. beams with spliced straight CFRP bars and with shear reinforcement within overlapping zone.

4. The CFRP Reinforcement

Closed FRP loops were manufactured by winding epoxy-saturated carbon fibre tows around a formed loop mould. Each loop was made from 25 continuous wraps of carbon fibre tow. The produced loops had square cross sections of 5×5 mm and a fibre volume fraction of 0.44. Straight bars were made from longer loops before the curved ends were cut off so as to ensure a fair comparison of performance. The properties of the carbon fibres tows are listed in Table 1. After initial ambient curing, the CFRP reinforcement was sand-coated using fine glass sand bonded with epoxy resin. This was followed by post curing at 60 °C for 12 hours. The glass transition temperature of the resulting CFRP was determined as T_g = 87 °C (using dynamic mechanical analysis and the peak value of tan δ) (ASTM, 2015).

Table 1. Manufacturer-specified properties of the carbon fibres tows used in the current study

Fibre type	**Number of filaments**	**Strength (MPa)**	**Young's modulus (GPa)**	**Cross-sectional area (mm^2)**	**Elongation (%)**	**Diameter (µm)**
Grafil-34-700WD	12000	4830	234	0.444	2.0	7

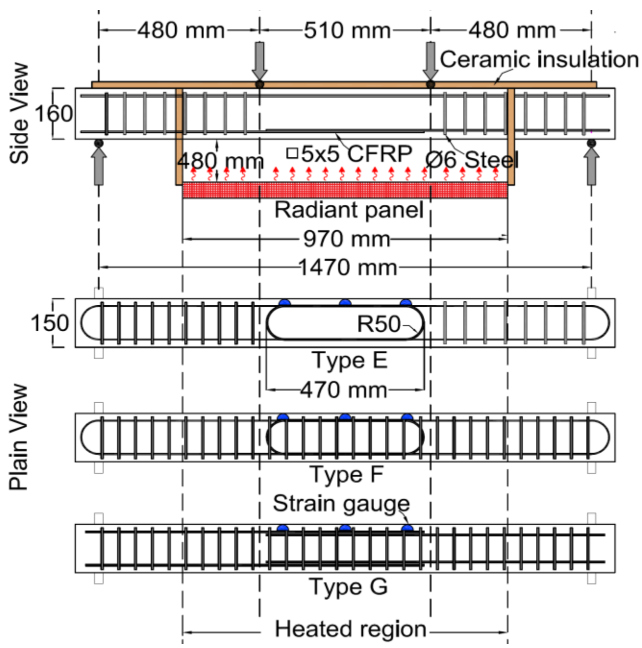

Fig. 1 – Test arrangement and specimen types (thermocouple locations shown in blue).

5. Test Arrangement

Two specimens of each type were tested to failure at ambient temperature in four-point bending at a loading rate of 2 mm/min. The other two specimens of each type were tested under a combination of sustained loading and severe heating using propane radiant panels. The sustained load during heating was 11.6 kN, which correspond to 35% of ambient ultimate strain and is greater than the cracking load of 7.5 kN (Fig. 2). Only Specimen E3 had a higher sustained load of 18.5 kN, which corresponds to 55% of the ambient ultimate tensile strain of the straight CFRP. Two radiant panels were used to heat the central 970 mm of the beam (Fig. 1). The remainder of beam was protected from heating using vermiculite board insulation (Fig. 1). The radiant panels were ignited once the sustained load had been reached and stabilised; the specimens were then heated until failure occurred under sustained load. Thermocouples were placed on the CFRP reinforcement at the middle and ends of splice zone to monitor reinforcement temperature. The beam displacement was measured using linear potentiometers placed at mid-span.

6. Results and Discussion

6.1. Unheated Tests

In the ambient tests, all specimens exhibited similar load-deflection responses. The corresponding failure loads and mechanisms of all specimens are given in Fig. 2. All beams failed by CFRP reinforcement rupture, apart from loop specimen (E1) which failed due to horizontal concrete shearing along the reinforcement overlapping zone. For specimen E1, when considering that the stress level in the reinforcement was 2808 MPa (approximated from the maximum measured strain value 0.012 (see Fig. 3) and Young's modulus (Table 1)) and the total area of the splice reinforcement, it is found that average shear stress generated by a CFRP loop is 1.4 MPa, which is about half of the theoretical concrete shear capacity of 2.9 MPa. However, the non-uniform distribution of forces (indicated by reinforcement strain gauge readings in Fig. 3) along the splice zone, with a peak at beginning of the splice, in addition to shear forces from adjacent point loads, may have contributed to localised shear stresses which may have initiated failure. The mid-span shear reinforcement in type F and G specimens provided extra confinement of CFRP reinforcement and increased shear interlock, which likely helped to prevent shear failure so that the reinforcement developed its full strength and failed by rupture. Rupture of both looped reinforcement and straight bars occurred directly adjacent to the splice zone ends, where the reinforcement ratio was reduced.

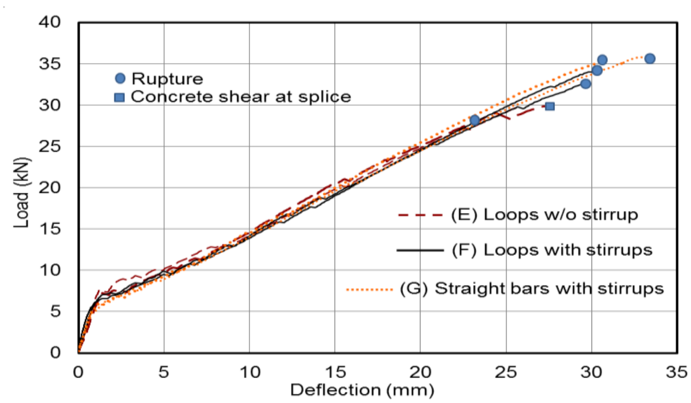

Fig. 2 – Load versus deflection responses for the ambient temperature control beam tests.

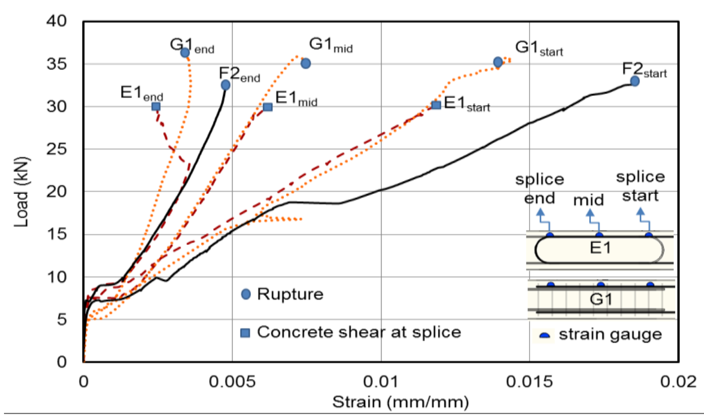

Fig. 3 – Load versus reinforcement strain responses for the ambient temperature control beam tests.

6.2 Heated Tests

During the heated tests the CFRP reinforcement was exposed to temperatures as high as 350 °C (Fig. 4), which is well above T_g (87 °C) of the resin. Fig. 4 shows the deflection versus heating time response for all heated specimens along with the corresponding failure modes. Whilst in ambient tests specimens with different reinforcement arrangements achieved similar failure loads, in the heated tests there was a significant difference in the time to failure. The initial response of all specimens during first 15mins of heating indicates combination of thermal bowing and CFRP bond degradation. In the case of straight bars shear transfer is the only mechanism of force transfer with concrete, thus pull out failure occurred after a comparatively short heating time (≈15 mins). Pull out failure coincided with CFRP temperatures exceeding T_g = 87 °C; this corroborates findings by others. (Bisby et al., 2005; Katz et al., 1999)

Specimens with CFRP loops (i.e. types E and F) developed higher strengths and failed by CFRP rupture, rather than bond failure, at longer durations of heating (57-76 mins). Rupture of the reinforcement indicates that the reinforcement was sufficiently anchored in the concrete for the FRP to reach its ultimate tensile capacity at elevated temperature. When the interlock and friction mechanisms of bond force transfer were lost due to softening of the resin, tensile forces can still be resisted through the carbon fibres in the loops; this is represented in Fig. 4 by a reduced deflection rate beyond about 20 minutes. Although the weaker section of the CFRP loops is the curved part of the FRP in the splice zone, additional strength is available in the curved section due to the presence of twice the total reinforcement in this location. The CFRP rupture location during heating was the same as in the ambient tests, i.e. just outside the splice zone where reinforcement ratio is reduced. The rupture load during heating was lower than at ambient temperature. As the resin softens it loses the ability to provide load sharing between the fibres. This causes unequal load distribution between individual fibres, initiating rupture. The progressive rupture of fibres is evidenced by an increased deflection rate leading eventually to failure Fig. 4.

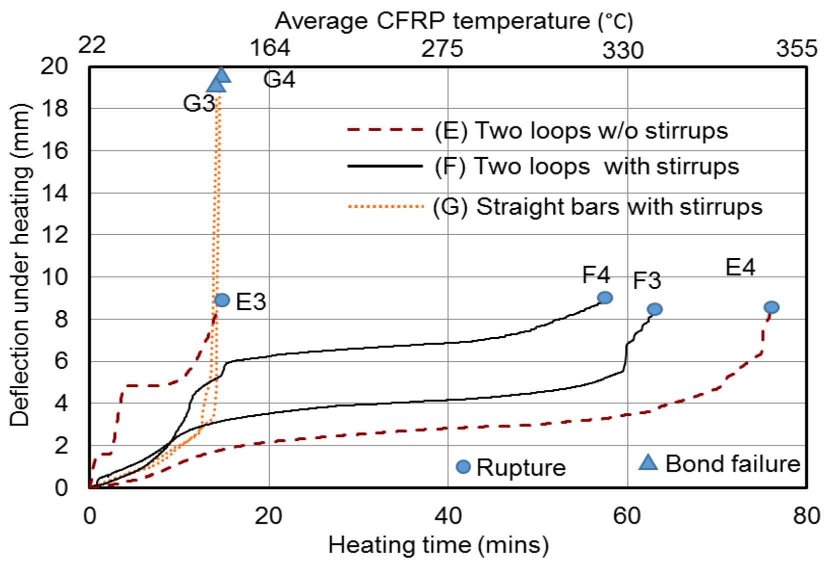

Fig. 4 – Deflection-time response under heating for different specimens

All but one specimen was tested under a sustained load of 35% of ultimate capacity. The value of sustained load 35% of ultimate capacity was chosen as it corresponded with maximum allowable serviceability deflection limit (*l*/240) as specified by ACI (2015). Specimen E3 was tested under a sustained load corresponding to 55% of the ambient temperature FRP ultimate strain; this is maximum sustained reinforcement stress level permitted by ACI (2015). Failure in specimen E3 occurred by CFRP rupture after comparatively short heating time. For this particular specimen (E3), after the sustained load of 18.5 kN was applied and followed by heating for 8 minutes, the radiant panels were switched off and the load was removed due to difficulties with propane flow. When the test was restarted the beam failed after about 9 minutes of heating. It was observed that crack openings increased significantly during the second heating attempt. This process is believed to have contributed to reducing the capacity of specimen. The reduced fire resistance of specimen E3 in comparison to other specimens with FRP loop can also be an indication that increasing load level result in reducing fire resistance time. Considering a fibre Young's modulus of 234 GPa and strain values in reinforcement (Fig. 2) at the level of sustained load of 11.6 kN, it can be concluded that under heating the loops rupture stress exceeded a yield stress of 500 MPa for a comparable steel reinforcing bar, with same cross-sectional area as the CFRP fibres in the FRP bars.

7. Conclusion

This study has examined the fire performance of new FRP reinforcement technique in which closed filament wound CFRP loops were utilised as tension reinforcement rather than straight bars. This was done in an attempt to overcome the bond sensitivity of FRP reinforcement in concrete at elevated temperatures, which hinders the widespread use of FRP reinforcement in concrete structures. A series of ambient and heated four-point bending tests was performed on beams reinforced with CFRP loops and others reinforced in traditional straight CFRP bars for comparison. At ambient temperature, specimens reinforced with both CFRP loops and straight bar reinforcement achieved similar values of failure load. All specimens, apart from one, developed sufficient bond stress for the reinforced to fail by FRP rupture.

At elevated temperatures, however, the benefit of CFRP loops became clear. The beams with straight bars failed due to reinforcement pull out after short time of fire exposure. Conversely, under same sustained load, specimens with CFRP loop reinforcement retained sufficient strength to carry the sustained applied load for a period up to four times longer than straight bars and failed by CFRP rupture. CFRP loops under heating were able to develop rupture stresses exceeding a comparable yield stress of 500MPa for steel reinforcement, because when the interlock and friction mechanisms of bond force transfer were lost due to softening of the resin, tensile forces in the reinforcement (FRP fibres) could still be resisted through the frictional anchorage of the CFRP fibres within the looped reinforcement links. This novel FRP reinforcement technology shows promise and, if further developed, may allow FRP reinforced concrete to be used in situations where its fire performance is important. It could thus help to remove one of the last remaining significant obstacles to CFRP's widespread use in buildings.

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